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Grinding temperature and energy ratio coefficient in MQL grinding of high-temperature nickel-base alloy by using different vegetable oils as base oil

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KEYWORDS

Base oil;
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Grinding force;
Grinding temperature;
MQL grinding;
Vegetable oil;
Viscosity

Abstract Vegetable oil can be used as a base oil in minimal quantity of lubrication (MQL). This study compared the performances of MQL grinding by using castor oil, soybean oil, rapeseed oil, corn oil, sunflower oil, peanut oil, and palm oil as base oils. A K-P36 numerical-control precision surface grinder was used to perform plain grinding on a workpiece material with a high-temperature nickel base alloy. A YDM–III 99 three-dimensional dynamometer was used to measure grinding force, and a clip-type thermocouple was used to determine grinding temperature. The grinding force, grinding temperature, and energy ratio coefficient of MQL grinding were compared among the seven vegetable oil types. Results revealed that (1) castor oil-based MQL grinding yields the lowest grinding force but exhibits the highest grinding temperature and energy ratio coefficient; (2) palm oil-based MQL grinding generates the second lowest grinding force but shows the lowest grinding temperature and energy ratio coefficient; (3) MQL grinding based on the five other vegetable oils produces similar grinding forces, grinding temperatures, and energy ratio coefficients, with values ranging between those of castor oil and palm oil; (4) viscosity significantly influences grinding force and grinding temperature to a greater extent than fatty acid varieties and contents in vegetable oils; (5) although more viscous vegetable oil exhibits greater lubrication and significantly lower grinding force than less viscous vegetable oil, high viscosity reduces the heat exchange capability of vegetable oil and thus yields a high grinding temperature; (6) saturated fatty acid is a more efficient lubricant than unsaturated fatty acid; and (7) a short carbon chain transfers heat more effectively than a long carbon chain. Palm oil is the optimum base oil of MQL grinding, and this base oil yields 26.98 N tangential grinding force, 87.10 N normal grinding force, 119.6 °C grinding temperature, and 42.7% energy ratio coefficient.

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Nomenclature and abbreviation

F_t (N) tangential grinding force
F_n (N) normal grinding force
V_w (mm/min) feed speed
λ (W/(m·°C)) thermal conductivity
c (J/(kg·°C)) specific heat
α (10^{-5}/°C) thermal expansion coefficient
ρ (kg/m^3) density
Q (J/s) grinding power
b (mm) grinding width
l (mm) grinding contacts arc
q''_{wb} (J/(m^2·K·s)) heat retained in the workpiece substrate
q''_c (J/(m^2·K·s)) heat carried away by abrasive dust
β constant
MQL minimum quantity lubrication
V_s (m/s) peripheral speed of grinding wheel
a_p (μm) cutting depth
m constant
d_s (mm) equivalent diameter of the grinding wheel
S (mm^2) contact area between the grinding wheel and the workpiece
q_{total} (J/(m^2·K·s)) total heat flux density
k_t (N) tangential grinding force on the unit cross section of the grinding edge
q''_f (J/(m^2·K·s)) heat carried away by grinding fluid
q''_g (J/(m^2·K·s)) heat transferred into abrasive particles
k (W/(m^2·K)) heat transmission coefficient
θ_{max} (°C) maximum grinding temperature increase
R ratio coefficient of energy transferred into workpieces

1. Introduction

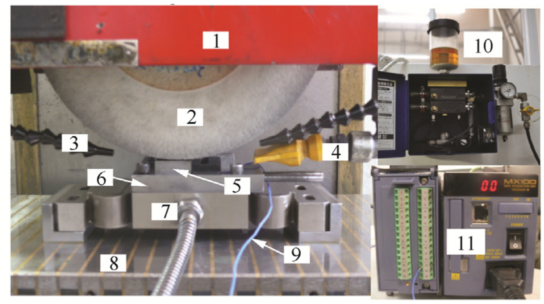
Grinding is one of the most basic and important techniques in the machining industry. The final precision and surface quality of most machine parts are determined by grinding technique. Grinding is currently the only machining technique applicable to most difficult-to-process materials.[1–3] During grinding, high energy consumption is necessary to eliminate unit material volume; thus, a high amount of heat is generated in the grinding zone. Grinding depth is also small; as a result, a larger specific grinding energy is produced by grinding than by cutting and milling.[4] Heat disperses to cuttings, tools, and workpieces. However, only a small proportion of grinding heat is removed by abrasive dust; heat is mostly transferred to grinding wheels and workpieces.[5] Grinding heat likely affects the surface quality and usability of workpieces.[1,2] In particular, an excessively high energy density of a workpiece surface burns the workpiece and deteriorates surface integrity.[6] During grinding, the grinding zone is often cooled and lubricated by traditional cooling via pouring and lubrication. A significant amount of grinding fluid is poured into the grinding zone[7] at usually 60 L/h per unit width of the grinding wheel.

With advances in grinding technology, cooling lubrication approaches have also been developed, improved, and optimized in terms of various aspects, such as energy conservation, emission reduction, eco-friendliness, and high efficiency.[8] However, pouring grinding cannot comply with green manufacturing and sustainable development in terms of environmental protection, low carbon emission, processability, and economical efficiency. Therefore, environmentally friendly, highly efficient, and low-energy-consuming grinding fluid or new cooling lubrication techniques and equipment should be developed to achieve various technical effects of cooling lubrication, high workpiece processing quality and precision, prolonged service life of grinding wheel, and low environmental pollution caused by grinding fluid.[3,9] Researchers[10] proposed a dry grinding technique. In dry grinding, grinding fluid is used, but high efficiency, high processing quality, prolonged grinding wheel service life, and a reliable grinding process can be maintained. Considering grinding wheel performance, machining tools, grinding dosage, and processing mode, we should integrate manufacturing techniques and materials science, as well as other subjects, such as information technology, electronics, and management.[11] However, dry grinding is characterized by several disadvantages, such as high grinding force and grinding temperature; as a consequence, low processing precision, short grinding wheel service life, geometric errors in workpieces, and poor processing quality are obtained.

In addition to dry grinding, MQL grinding is a green machining technique.[12] Technicians in this field of machining as a substitute for traditional coolant supply method.[13] Compressed air and minimum lubricant are initially mixed and evaporated; afterward, the compressed air and minimum lubricant are sprayed into the processing zone to lubricate the grinding position effectively between the grinding wheel and the workpiece.[14,15] The grinding fluid dosage in MQL is only 30–100 mL/h per unit width of grinding wheel[16] or approximately 1/1000 of the grinding fluid dosage in pouring grinding. Hadad et al.[17] investigated 100Cr6 grinding by using MQL technique with an overhead thermocouple to measure grinding temperature. Hadad et al.[17] found that MQL consumes 7%–10% less energy than dry grinding. Dhar et al.[18] reported that MQL generates 5%–15% smaller grinding force than dry grinding; thus, the service life of cutters is prolonged. Gaitondea et al.[19] found that MQL achieves a higher workpiece surface processing quality than dry grinding. Mao et al.[20] studied heat transfer on the workpiece surface during MQL grinding; in this method, the grinding zone is divided into four regions according to different microdroplet heat transfer mechanisms of workpiece surface temperature: non-boiling heat transfer region, nucleate-boiling heat transfer region, transition-boiling heat transfer region, and stable film-boiling heat transfer region. The heat transfer mechanism on the workpiece surface during MQL grinding is more credible than that of pouring grinding. Tawakoli et al.[21] discussed the effect of grinding parameters on workpiece surface quality. With optimum grinding fluid dosage and feed liquid parameters, MQL grinding achieves a greater workpiece surface quality but a lower tangential grinding force and specific grinding energy than pouring grinding. Barczak et al.[16] compared the grinding power, grinding force, grinding temperature, and surface roughness of MQL grinding with those of pouring grinding and dry grinding. Barczak et al.[16] found that MQL grinding is superior to pouring grinding in terms of grinding force and grinding power but inferior in terms of workpiece surface roughness and residual stress at an appropriate material removal rate. Silva et al.[22] compared workpiece surface integrity, specific grinding energy, and grinding wheel wear via dry grinding, pouring grinding, and MQL grinding. Silva et al.[22] concluded that the grinding temperature further increases to a certain extent in MQL grinding compared with that in dry grinding. MQL provides a more effective lubrication but exhibits poorer cooling effect and workpiece surface integrity than pouring grinding.

Although MQL grinding exhibits some advantages over pouring grinding, the former produces abundant oil mists in air; as a result, human health is threatened. In a previous study,[23] the leakage and volatilization of grinding fluid cause pollution and inflict hazards to the environment and the human body. Therefore, vegetable oils have been used as base oils in MQL. Vegetable oils are characterized by a higher boiling point and molecular weight than mineral oils; thus, the wastes of the former are significantly reduced through atomization and gasification. Steigerwald[24] reported that glyceride in vegetable oil is easily hydrolyzed, and the unsaturated double bond in the ester chain easily undergoes β-oxidation upon microbial attacks; as such, vegetable oils are biodegradable. Zhang et al.[25] investigated nanoparticle efflux MQL grinding by using soybean oil, rapeseed oil, and palm oil as base oils. Zhang et al.[25] found that soybean oil-based MQL grinding yields greater performances than the two other vegetable oils. Nurul et al.[26] examined the surface roughness and surface integrity of MQL grinding by using palm oil, sesame oil, olive oil, and coconut oil as base oils. Cetin et al.[27] analyzed the grinding surface roughness of AISI 304L steel by using sunflower oil and rapeseed oil as base oils. Mohamed et al.[28] used castor oil as the base oil of MQL grinding to grind hardened stainless steel and subsequently explored grinding performances, such as surface roughness and grinding force. Le et al.[29] used peanut oil as the base oil of MQL grinding to cut the difficult-to-process 9CrSi steel; Le et al.[29] found that the processed workpiece is characterized by a relatively integrated surface roughness. Jain and Bisht[30] aimed to replace the cutting fluid with non-edible vegetable mineral oils, such as rapeseed oil and Karanja tree oil, in metal cutting. Rahim and Sasahara[31–33] investigated metal cutting by using palm oil and synthetic ester as MQL base oils and compared their corresponding grinding performances. Rahim and Sasahara[31–33] discovered that the microhardness, surface roughness, surface defect, and areal deformation of a workpiece in palm oil-based MQL grinding are greater than those of synthetic ester-based MQL grinding. Rahim and Sasahara[31–33] also found that the carbon chain length of vegetable oils influence processing temperature to a certain extent.

Although studies[34–37] have discussed and confirmed that vegetable oils can be used as base oils of MQL grinding and can increase production efficiency, service life of cutters, and workpiece surface processing quality, only a few studies have comprehensively investigated vegetable oils. A comparative analysis of many vegetable oils under the same grinding conditions has yet to be performed. This study theoretically analyzed and experimentally investigated grinding temperatures



1—Wheel cover; 2—Wheel; 3—Supply nozzle of MQL grinding liquid; 4—Supply nozzle of flood grinding liquid; 5—Workpiece; 6—Fixture; 7—YDM-III99 grinding 3D dynamometer; 8—Workbench; 9—Thermocouple wire; 10—Bluebe minimum quantity oil supply system; 11—Thermocouple grinding temperature measuring device

Fig. 1 Surface grinding setup, MQL fluid delivery system, and grinding temperature measuring device.

and energy ratio coefficients through the MQL grinding of a high-temperature nickel-base alloy by using different vegetable oils as base oils.

2. Experimental equipment and conditions

2.1. Equipment

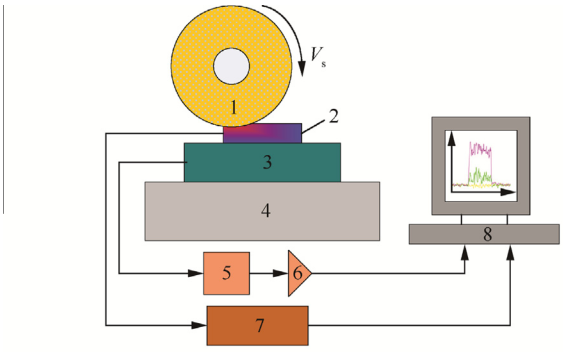
The experiment was conducted using a K-P36 numerical-control precision surface grinder. The main technological parameters were as follows: principal axis power of 40 kW; highest rotating speed of 2000 r/min; workbench driving motor power of 5 kW; grinding scope of 600 mm × 300 mm; corundum wheel size of 300 mm × 20 mm × 76.2 mm; particle size of 80#; highest peripheral speed of grinding wheel of 50 m/s; vegetable oil transfer device Bluebe minimum quantity oil supply system; and measuring cell YDM–III 99 three-dimensional dynamometer. The experimental device setup is shown in Fig. 1. Grinding temperature was measured using a clip-type thermocouple. The measured experimental data are shown in Fig. 2.

2.2. Materials

The grinding workpiece used in this study was a high-temperature nickel base alloy GH4169. The base oils of MQL included castor oil, soybean oil, rapeseed oil, corn oil, peanut oil, palm oil, and sunflower oil. Table 1 lists the chemical composition of GH4169, and Table 2 shows its performance parameters. Table 3 presents the basic properties of the seven different base oils of MQL. The viscosities of these seven vegetable oils were measured using a Brookfield DV2T viscometer at 25 °C. Fig. 3 shows the obtained viscosities of vegetable oils. Table 4 summarizes the corresponding viscosities.

2.3. Experimental conditions

The grinding parameters in the experiment are shown in Table 5.



1—Wheel; 2—Workpiece; 3—Grinding 3D dynamometer; 4—Workbench; 5—Grinding force signal collection device; 6—Charge amplifier; 7—Thermocouple temperature signal collectors; 8—Computer

Fig. 2 Experimental data measuring schematic.

2.4. Theoretical analysis

A YDM–III 99 three-dimensional dynamometer was used in each experiment to measure and record normal force, tangential force, and axial force. The measured sample frequency of grinding force was 1 kHz. The grinding force signal after sampling was filtered using the "Dynamic Grinding Force Test System" software to obtain the grinding force image document and grinding force data document. A total of 100 data points were selected from the stable zone of grinding force in each direction. Grinding temperature was measured using a clip-type thermocouple. Temperature was determined throughout the grinding process to draw the grinding temperature curve. Furthermore, 100 data points were chosen to calculate the average grinding temperature. During data processing, the ratio coefficient of energy transferred into the workpiece during the grinding process was calculated from the average grinding force and average grinding temperature.

2.4.1. Vegetable oil classification

Tables 3 and 4 list the basic properties of the seven vegetable oils used in MQL grinding. The viscosity of castor oil is 0.535 Pa·s, which is approximately 10 times higher than that of other vegetable oils. Moreover, the castor oil content reaches as high as 90.85%. Therefore, castor oil is classified into the first group. Soybean oil, corn oil, sunflower oil, and peanut oil are classified into the second group because these oils contain oleic acid, linoleic acid, palmitic acid, and stearic acid; these oils are also characterized by similar total contents, viscosities, and no excessively high fatty acid contents. Rapeseed oil contains a high amount of erucic acid but a relatively low amounts of oleic acid, linoleic acid, and stearic acid; thus, rapeseed oil is classified into the third group. Palm oil is composed of the highest palmitic acid content and viscosity among the seven vegetable oils; thus, palm oil is classified into the fourth group.

2.4.2. Grinding force

Grinding force is generally represented by tangential grinding force (F_t) and normal grinding force (F_n). Tangential grinding force (F_t) can be further divided into tangential cutting force ($F_{t,c}$) and tangential sliding friction force ($F_{t,sl}$). Normal grinding force (F_n) can be divided into normal cutting force ($F_{n,c}$) and normal sliding friction force ($F_{n,sl}$).[38] Grinding force is expressed as follows[39]

$$F_t = F_{t,c} + F_{t,sl} \tag{1}$$

$$F_n = F_{n,c} + F_{n,sl} \tag{2}$$

Lubricating properties can be expressed as the ratio of the normal grinding force and the tangential grinding force (F_n/F_t) in the grinding interface. As F_n/F_t increases, the grinding wheel becomes less sharp than the initial condition. This result shows that the grinding interface elicits a poor lubrication effect.[1]

Grinding force is the sum of the grinding forces of single effective abrasive particles in the grinding wheel/workpiece contact zone. F_t can be expressed as follows[38]:

$$F_t = 2^m \lambda^{m-1} k_t V_s^{-m} a_p^{\frac{m+1}{2}} d_s^{\frac{1-m}{2}}. \tag{3}$$

2.4.3. Grinding heat

Grinding heat is generated by sliding friction, ploughing, and cutting between abrasive particles on the grinding wheel and the workpiece surface. Grinding heat is an important factor influencing the grinding performance. When the grinding surface temperature exceeds a critical value, grinding heat causes thermal surface damages, such as oxidation, burning, residual stress, and cracks. These conditions result in poor wear resistance, fatigue resistance, short service life and reliability, or even direct scrapping of parts.[40] Therefore, lowering grinding temperature of the grinding zone is of utmost concern during grinding. Grinding heat should also be investigated to lower grinding temperature quickly and effectively during processing and to improve processing quality and part precision.

The heat source model in plane grinding is a problem related to the effect of a moving surface heat source with an infinite width and a finite length on a semi-infinite heat conductor. The total heat flux density (q_{total}) generated by the input energy of grinding wheel on the grinding zone is expressed as follows[1]:

$$q_{total} = \frac{Q}{S} = \frac{F_t V_s}{lb} \tag{4}$$

where q_{total} is the total heat flux density, J/(m^2·K·s).

2.4.4. Energy distribution and energy ratio coefficient

Outwater and Shaw[41] proposed that heat during grinding comes from three interfaces: abrasive particle/workpiece interface, abrasive particle/abrasive dust interface, and shearing surface between workpiece and abrasive dust. Abrasive

Table 1 Chemical components of GH4169.

Element	Ni	C	Cr	Nb	Mo	Ti	Co	Al	Mn	Cu	Fe
Ingredient (%)	50–55	0.08	17–21	5.25	3.1	0.96	1.0	0.95	0.35	0.3	Bal.

Table 2 Material performance parameters of GH4169.

Temperature (°C)	Thermal conductivity λ (W/(m·°C))	Specific heat c (J/(kg·°C))	Thermal expansion coefficient α (10^{-5}/°C)	Density ρ (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Yield strength (MPa)
25	13.4	435	–	8240	200	0.3	550
100	14.7	458	1.18				
200	15.7	467	1.30				
300	17.8	481	1.35				
400	18.3	494	1.41				
500	19.6	515	1.44				
600	21.2	539	1.48				
700	22.8	573	1.54				

Table 3 Properties of the seven trace lubricating base oils.

Parameter	Castor oil	Soybean oil	Rapeseed oil	Corn oil	Peanut oil	Sunflower oil	Palm oil
Oleic acid (%)	2.82	23	5.92	32.55	40.84	28.76	36.8
Linoleic acid (%)	3.74	52.4	23.63	51.4	34.54	50.48	10.2
Palmitic acid (%)	0.72	8.9	2.63	1.94	11.92	11.24	45.1
Stearate (%)	0.64	3.8	11.72	13.27	4.3	6.48	4.8
Eicosanoids (%)	–	–	2.92	–	1.38	–	–
Erucic acid (%)	–	–	43.63	–	–	–	–
Vaccenic (%)	–	–	4.99	–	–	–	–
Linolenic acid (%)	–	10.6	3.34	–	–	–	–
Ricinoleic acid (%)	90.85	–	–	–	–	–	–
Saponification value (%)	181	192	193	190	192	189	193
Saturated fatty acids (%)	52	15	6	14	21	11	35
Monounsaturated fatty acids (%)	37	24	58	29	49	19	15
Polyunsaturated fatty acids (%)	11	61	36	54	30	70	50

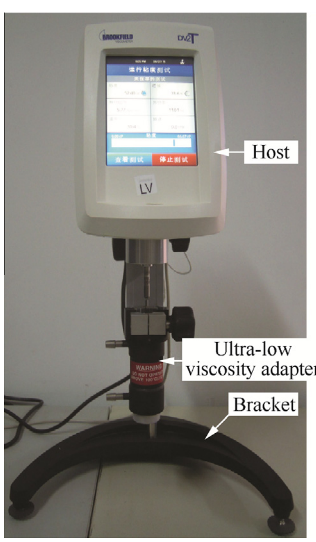


Fig. 3 Physical map of Brookfield DV2T viscometer.

particle/workpiece interface and abrasive particle/abrasive dust interface generate friction heat, whereas the shearing surface between the workpiece and the abrasive dust, as well as the abrasive particle/workpiece interface, produces plastic deformation that generates high amounts of heat. On the basis of different heat conductivity coefficients of the workpiece material, abrasive particle, and grinding fluid, heat is transferred to the workpiece substrate, abrasive particles, abrasive dust, and grinding fluid.

In pouring grinding, some of the heat is carried away by grinding fluid q''_{f}, some of the heat is retained in the workpiece substrate q''_{wb}, some of the heat is transferred into abrasive particles q''_{g}, and some of the heat is carried away by abrasive dust q''_{c} with the heat convection of grinding fluid. Therefore, heat distribution with the use of grinding fluid can be expressed as follows:

$$q''_{\mathrm{total}} = q''_{\mathrm{wb}} + q''_{\mathrm{g}} + q''_{\mathrm{c}} + q''_{\mathrm{f}} \tag{5}$$

After heat distribution on the grinding interface is determined, specific energy distribution is detected. Grinding emphasizes on the integrity of the workpiece surface after processing. Therefore, calculating the energy ratio coefficient and

Table 4 Viscosities of the seven vegetable oils.

Vegetable oil	Viscosity (Pa·s)
Castor oil	0.535
Soybean oil	0.042
Rapeseed oil	0.051
Corn oil	0.047
Peanut oil	0.053
Sunflower oil	0.051
Palm oil	0.062

Table 5 Grinding parameters.

Grinding parameters	Value
Grinding pattern	Plain grinding
Peripheral speed of grinding wheel V_s (m/s)	30
Feed speed V_w (mm/min)	3000
Cutting depth a_p (μm)	10
MQL flow rate (mL/h)	50
MQL nozzle distance (mm)	12
MQL nozzle angle (°)	15
MQL gas pressure (MPa)	0.6

heat transferred into the workpiece is important for adopting appropriate cooling lubrication measures to prevent grinding burning. Energies transmitted into the workpiece is[42]:

$$q_{wb} = \frac{kV_w^{1/2}}{\beta\alpha_w^{1/2}\ a_p^{1/4}\ d_s^{1/4}}\theta_{max} \tag{6}$$

where k is the heat transmission coefficient, W/(m^2·K).

In Table 2, the thermal conductivity of the high-temperature nickel base alloy changes with temperature; likewise, the heat transfer coefficient changes; this parameter is determined using the grinding temperature. The average value of the heat transfer coefficient of two temperatures adjacent to the grinding temperature was used to improve its accuracy. β is a constant determined by the shape of heat source and is generally set at 1.06; α is the thermal diffusivity (m^2/s), $\alpha = \lambda/(\rho c)$. As a result, the ratio coefficient R of energy transferred into the workpiece is expresses as follows[5]:

$$R = q_{wb}/q_{total} \tag{7}$$

3. Results and discussion

3.1. Experimental scheme

In this experiment, soybean oil, corn oil, peanut oil, sunflower oil, rapeseed oil, palm oil, and castor oil were used as the base oils of MQL grinding. The corresponding grinding force, grinding temperature, and energy ratio coefficient were compared to analyze their MQL grinding performances.

3.2. Results

3.2.1. Grinding force

Fig. 4 shows the filtered images of grinding force by using castor oil, peanut oil, rapeseed oil, and palm oil as the base oils of MQL grinding.

As a very important technical parameter in grinding process, grinding force can indicate not only the grinding state but also the lubrication state. Under fixed grinding conditions, normal cutting force, tangential cutting force, and normal sliding friction force on the grinding surface are constant. Therefore, when the lubrication state changes, the sliding friction decreases, and the tangential grinding force is reduced proportionally.

Fig. 5 illustrates the tangential grinding force and normal grinding force of the seven vegetable oils used as the base oils of MQL grinding. Castor oil yields the minimum tangential grinding force (24.33 N) and normal grinding force (76.83 N); palm oil exhibits the minimum tangential grinding force (26.98 N) and normal grinding force (87.10 N). The tangential grinding force and normal grinding force of rapeseed oil are 31.88 and 102.53 N, respectively. The tangential grinding forces of soybean oil, sunflower oil, corn oil, and peanut oil are 31.54, 31.34, 33.91, 31.10 N, respectively; their normal grinding forces are 104.24, 101.88, 99.85, 91.37 N, respectively. The tangential grinding forces of palm oil, rapeseed oil, soybean oil, sunflower oil, corn oil, and peanut oil are 11.0%, 33.5%, 29.6%, 28.8%, 39.4%, and 27.8% higher than that of the castor oil, and their normal grinding forces are 13.4%, 31.0%, 35.7%, 32.6%, 30.0% and 18.9% higher, respectively. The tangential grinding forces of rapeseed oil, soybean oil, sunflower oil, corn oil and peanut oil are 18.2%, 16.9%, 16.2%, 25.7%, and 15.3% higher than that of palm oil, respectively; their respective normal grinding forces are 17.7%, 19.7%, 17.0%, 14.6%, and 4.9% higher than that of palm oil.

3.2.2. Grinding temperature

The thermal damages caused by high grinding temperatures greatly influence workpiece quality and limit productivity.[5] Hence, the main factors influencing grinding temperature should be understood. Grinding parameters significantly affect grinding temperature. The effective cooling and heat transmission influences of grinding fluid are other relevant factors.

Fig. 6 shows the variation curves of grinding temperature over time in MQL grinding by using seven different vegetable oils as base oils. Castor oil-based MQL grinding achieves the highest grinding temperature, whereas palm oil-based MQL grinding yields the lowest grinding temperature.

Fig. 7 displays the average grinding temperature of MQL grinding based on seven vegetable oils. The highest grinding temperature (176 °C) is achieved by castor oil, and the lowest grinding temperature (119.6 °C) is contributed by palm oil. The grinding temperatures of rapeseed oil, soybean oil, corn oil, sunflower oil, and peanut oil are 143.4, 143.5, 139.6, 139.3, 138.4 °C, respectively. The grinding temperatures of palm oil, soybean oil, rapeseed oil, corn oil, sunflower oil, and peanut oil are 32.0%, 18.5%, 18.5%, 20.7%, 20.9%, and 21.4% lower than that of castor oil.

3.2.3. Ratio coefficient of energy transferred into workpieces

The energy distribution of the workpiece is a key factor used to calculate the grinding temperature and controlling thermal damages. The ratio coefficients of energy transferred into the workpieces is an important parameter to determine the effect of grinding temperature transfer and the cooling effect of grinding fluid.

The ratio coefficients of energy transferred into workpieces in MQL grinding based on seven different vegetable oils were calculated using Eqs. (4), (6), and (7). The results are shown in Fig. 8. Castor oil yields the highest energy ratio coefficient (69.3%); this finding is followed by palm oil with an energy ratio coefficient of 52.3%, which is 24.5% lower than that of castor oil. Soybean oil presents the lowest energy ratio coefficient (42.7%), which is 38.4% lower than that of castor oil and 18.4% lower than that of palm oil. The ratio coefficients of rapeseed oil, sunflower oil, peanut oil, and corn oil are 49.1%, 48.8%, 48.1%, and 47.8%, which are 29.1%, 29.6%, 30.6%, and 31.0% lower than that of castor oil. These parameters are also 6.1%, 6.7%, 8.0%, and 8.6% lower than that of

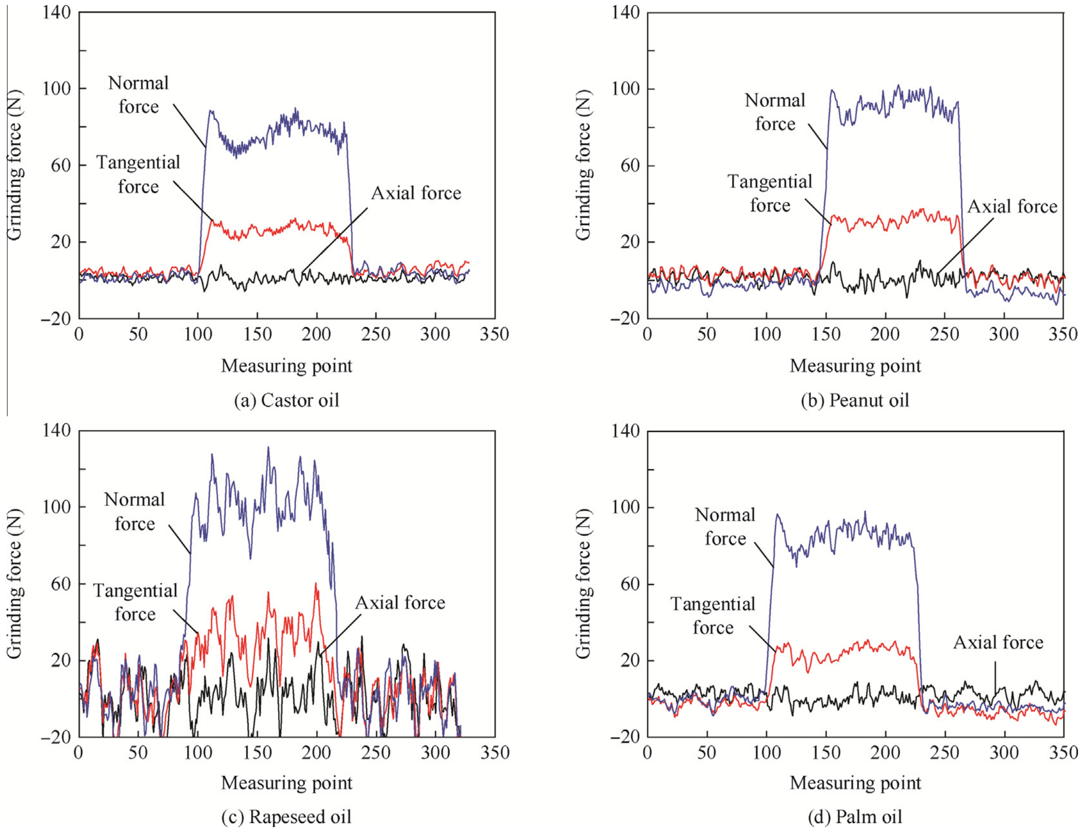


Fig. 4 Signal graph of the measured grinding force of the four kinds of vegetable oils in MQL grinding.

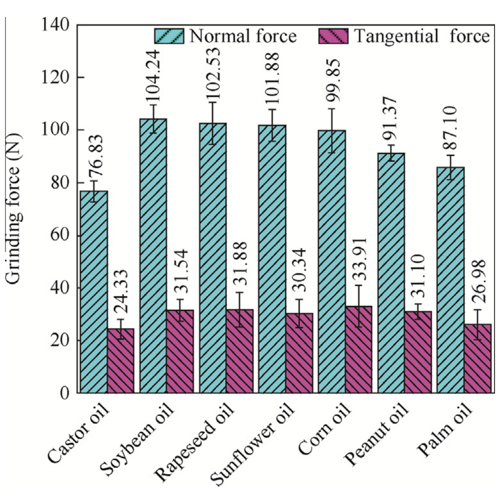


Fig. 5 MQL grinding force for seven kinds of vegetable oil.

palm oil but 15.0%, 14.3%, 12.6%, and 11.9% higher than that of soybean oil, respectively.

3.3. Discussion

3.3.1. Grinding force

Based on tangential and normal grinding forces, castor oil as the base oil of MQL grinding exhibits the optimum lubrication effect mainly because the lubricating oil film formed by castor oil on the grinding zone shows a good anti-friction and carrying capacity (see Fig. 9). This phenomenon can be explained on the basis of the following three aspects:

(1) Effect of the viscosity of vegetable oils. The viscosity of castor oil at 25 °C is 0.535 Pa·s; this finding indicates that castor oil is very thick. In MQL grinding, high-viscosity castor oil molecules exhibit poor liquidity, and a layer of dense protection film is formed on the workpiece surface after castor oil is sprayed onto the grinding zone. This protection film exhibits a high anti-friction and carrying capacity, reducing friction between the grinding wheel and the workpiece, and significantly decreases grinding force.

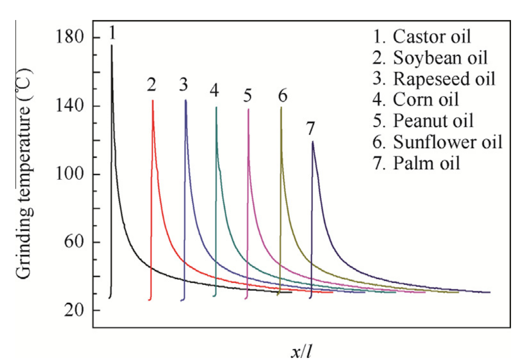


Fig. 6 Grinding temperature graph for seven kinds of vegetable oil.

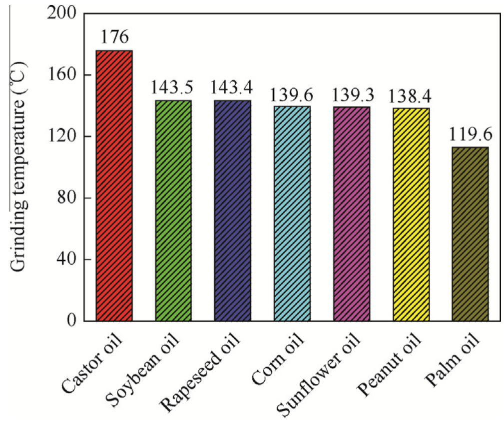


Fig. 7 Grinding temperature of the seven kinds of vegetable oils in MQL grinding.

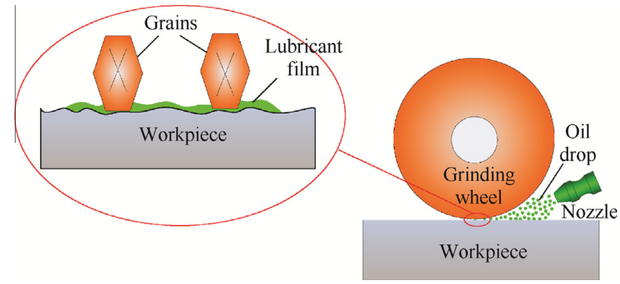


Fig. 9 Schematic of the antiwear and load-carrying capacity of lubricant film.

(2) Effect of the physical adsorption film formed by fatty acids. The lubrication condition can be divided into boundary lubrication, mixed lubrication, and hydrodynamic lubrication on the basis of the formation of oil film and the extent of the friction pair surface separation. Boundary lubrication is a critical state before liquid friction transitions into dry friction (direct contact with the friction surface).[43] The grinding fluid in the grinding zone is difficult to maintain in the lubrication state but is in the boundary lubrication state because of large or impact vibration loads.[25] The formation of this physical adsorption film is related to the oiliness of vegetable oils and carbon chain length in fatty acids. On the one hand, vegetable oils contain polar atoms, such as S, O, N, and P, or polar groups, such as –OH, –COOH, –COOR, –COR, –CN, –CHO, –NCS, $-NH_2$, $-NHCH_3$, $-NH_3$, and –NROH). These polar atoms or groups yield a strong affinity to the workpiece surface and physically adsorb molecules on the workpiece surface through Van der Waals forces to form the physical adsorption film. The physical adsorption film can reduce friction; thus, grinding force is decreased. On the other hand, the molecular carbon chain length of fatty acids in vegetable oils influences the adsorption durability of the physical adsorption film. A longer carbon chain corresponds to a stronger adsorption film.[44] The ricinoleic acid content in castor oil reaches 90.85%, and two polar groups, namely, –OH and –COOH, are found in ricinoleic acid; as a result, the formed physical adsorption film exhibits high strength and durability. Therefore, castor oil-based MQL grinding achieves the minimum grinding force. Zhang et al.[25] discovered that carbon chain length is not the main factor influencing the lubrication capability of the physical adsorption film. This finding can also be confirmed by the experimental grinding force in this study. For example, rapeseed oil contains 43.63% erucic acid, and palm oil contains 45.1% palmitic acid. These two fatty acids are characterized by basically the same content, and other fatty acids in these two vegetable oils are similar in terms of variety and content. Fig. 10 shows that the carbon chain of erucic acid is longer than that of palmitic acid. In theory, rapeseed oil-based MQL grinding yields a smaller grinding force than palm oil-based MQL grinding. However, an opposite result was observed in the experiment. Thus, the carbon chain length is not the main factor influencing the lubrication capability of the physical adsorption film.

(3) Effect of metal saponification effect. Saturated fatty acids and a metal friction surface chemically react to form a layer of a fatty acid soap adsorption film. This film can be either monomolecular or polymolecular. The film seems vertical because fatty acids are adsorbed onto the metal surface. With molecular attractions, molecules are densely distributed on the metal surface to prevent mutual friction between metal surfaces; thus, metal friction and wear are reduced. The carbon content influences total adsorption energy. In general, the total adsorption energy and strength of the adsorption film are proportional to the carbon content. However, an adequate carbon content is necessary to obtain the maximum-density adsorption film. When the carbon content increases, the adsorption film reaches its maximum strength and density. The physical adsorption film formed by saturated fatty acid is unrelated to the number of carbon atoms in this molecule if more than 16 carbon atoms are present. For instance, C18 stearic acid and C22 docosanoic acid exhibit the same anti-wear and anti-friction properties. The arrayed adsorption film becomes less dense with a polar unsaturated bond in the same series of acids because of the adsorption effect of olefinic bond, accompanied with poor strength and

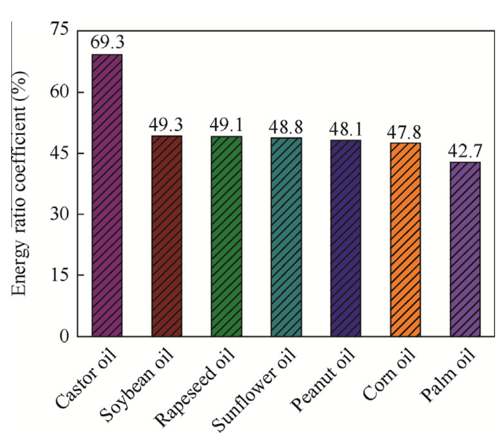


Fig. 8 Ratio coefficients of energy transferred into workpieces for the seven kinds of vegetable oil used in MQL grinding.

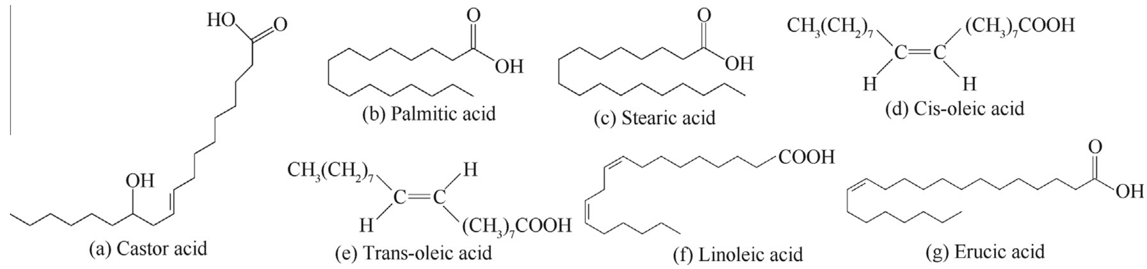


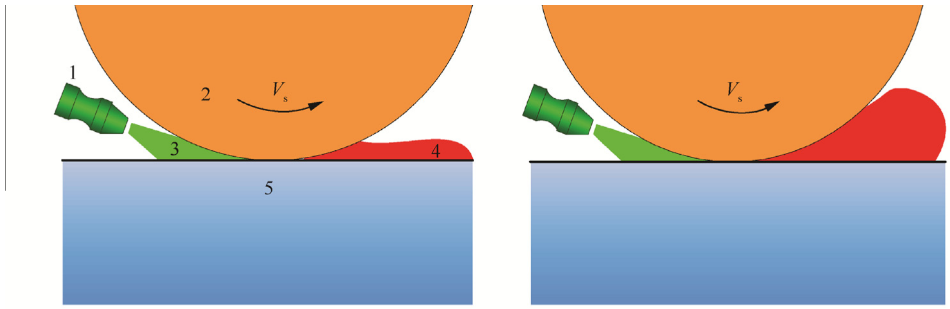
Fig. 10 Molecular structures of several fatty acids.

lubrication capability. Under this condition, transverse cohesion between molecules, or mutual attraction, is very important. The adsorption film formed by long-chain docosanoic acid is stronger than that of the short-chain stearic acid because cohesion is proportional to the number of carbon atoms. Therefore, docosanoic acid is a more efficient lubricant than stearic acid.[45] In Table 3, the highest saturated fatty acid content in castor oil is 52%. Therefore, the adsorption film formed through saponification between saturated fatty acid in castor oil and the workpiece surface yields a higher density than that in other vegetable oils. Furthermore, the carbon chain of castor oil is longer than that of the other vegetable oils; as a result, a stronger adsorption film is formed in relation to castor oil than to other vegetable oils. With the same carbon content, saturated fatty acid is a more efficient lubricant than unsaturated fatty acids. Therefore, castor oil generates the smallest grinding force. Furthermore, the saturated fatty acid content in palm oil is 35%, which is higher than that in the five other vegetable oils. As such, the grinding force of palm oil-based MQL grinding is lower than that of the five other vegetable oils.

3.3.2. Grinding temperature

The grinding temperatures of soybean oil and rapeseed oil are 20% higher than that of palm oil. Likewise, the grinding temperatures of corn oil, sunflower oil, and peanut oil are 16.7%, 16.5%, and 15.7% higher than that of palm oil, respectively. The MQL grinding temperatures of soybean oil, corn oil, sunflower oil, and peanut oil are basically similar. Considering the fatty acid content and viscosity of these four vegetable oils (Tables 3 and 4), we may conclude that vegetable oils with slightly different fatty acid contents but similar viscosities likely exhibit similar maximum grinding temperatures in MQL grinding; thus, these vegetable oils elicit similar cooling effects. In addition, soybean yields the smallest viscosity (0.042 Pa·s), with nearly a 0.010 Pa·s difference with the three other vegetable oils. However, soybean shares the same grinding temperature with the three other vegetable oils. This finding may be related to the fluidity between vegetable oil molecules at high temperature. When vegetable oil and compressed air are simultaneously sprayed onto the grinding zone, grinding occurs and generates a high grinding temperature, which reduces the viscosity of vegetable oil to a certain extent and enhances their fluidity. Moreover, the compressed air accelerates vegetable oil flow; thus, vegetable oils fail to form a dense and effective protection film layer on the grinding wheel and grinding surface of the workpiece. Consequently, a relatively higher grinding temperature is generated. Soybean oil, corn oil, sunflower oil, and peanut oil also exhibit similar viscosities and fluidities in MQL grinding. Carbon chain length and polar groups in vegetable oils influence viscosity.[33,46] For instance, a long carbon chain corresponds to a high viscosity of vegetable oils. The viscosity of vegetable oils greatly affects grinding temperature. Vegetable oils with a high viscosity generate higher grinding temperature than those with a low viscosity. Although rapeseed oil contains as much as 43.63% erucic acid and long carbon chains, its viscosity is not very high. This characteristic is possible because rapeseed oil also contains other kinds of fatty acids with higher contents than erucic acid. Therefore, erucic acid in rapeseed soil slightly affects its viscosity. Therefore, the grinding temperature of rapeseed oil is similar to those of the four vegetable oils.

The comparison results of tangential grinding force and normal grinding forces demonstrated that castor oil generates the smallest tangential and normal grinding forces but yields the highest grinding temperature. Soybean oil, rapeseed oil, corn oil, peanut oil, and sunflower oil exhibit relatively higher grinding forces but generate smaller grinding temperatures. This finding may be attributed to the properties of vegetable oils. Ricinoleic acid significantly affects the viscosity of castor oil because castor oil contains 90.85% ricinoleic acid with two polar groups and numerous carbon atoms. Among the seven vegetable oils, castor oil yields the highest viscosity. A high viscosity corresponds to a poor molecular fluidity. In MQL grinding, a low amount of castor oil sprayed on the grinding zone likely forms a dense lubrication film; as a result, a small grinding force is generated. However, castor oil cannot leave the grinding zone with the flow of compressed air after heat exchange occurs in the grinding zone because of its poor fluidity. Nevertheless, high-temperature castor oils accumulate in the grinding zone; thus, poor cooling and heat transfer effects are elicited (Fig. 11(b)). As a result, the temperature of the workpiece surface increases continuously. Hence, castor oil-based MQL grinding yields the highest grinding temperature. Although tangential grinding force decreases and the total energy generated in the grinding zone is reduced, the grinding energy transferred into the workpiece and the grinding temperature increase because of the high viscosity of castor oil; this condition decreases the grinding energy transferred into the cooling medium q''_f. Other vegetable oils with low viscosities possibly leave the grinding zone with compressed air after grinding heat is absorbed (Fig. 11(a)). Low-viscosity vegetable oils elicit a greater heat transfer effect than castor oil; as a result, low grinding temperatures are obtained. Grinding temperature can be further accounted for the smallest grinding



(a) Low viscosity vegetable oil heat capacity schematic (b) High viscosity vegetable oil heat capacity schematic

1—Nozzle; 2—Grinding wheel; 3—Heat transfer fluid before grinding; 4—Heat transfer fluid after grinding; 5—Workpiece

Fig. 11 Heat transfer capacity of vegetable oils with different viscosities.

force exhibited by castor oil-based MQL grinding. When castor oil is used, a good lubrication capacity is observed and the highest workpiece temperature is obtained; as a consequence, the workpiece material in the cutting zone is softer than that when other oils are used. Therefore, the workpiece material is easily deformed plastically and the chip is easily removed.

The similar grinding temperatures of soybean oil, rapeseed oil, corn oil, peanut oil, and sunflower oil can be attributed to their fatty acid contents. Saturated fatty acids are more efficient lubricants than unsaturated fatty acids in terms of the effect of metal saponification on grinding force. Table 3 shows that unsaturated fatty acids in the five vegetable oils account for more than 80% of the total fatty acids; thus, poor lubrication effects are elicited between the workpiece and grinding wheel, and a high grinding force is generated. The grinding wheel/workpiece interaction is more intense when these five vegetable oils are used as the base oil of MQL grinding than when castor oil and palm oil are used; as a result, the grinding temperature of the former is higher than that of the latter. Therefore, viscosity affects grinding force and grinding temperature to a greater extent than fatty acid variety and content in vegetable oils.

Figs. 5 and 7 reveal that palm oil-based MQL grinding generates a relatively low grinding force and grinding temperature. The viscosity of palm oil is 0.062 Pa·s, which is higher than those of soybean oil, rapeseed oil, corn oil, sunflower oil, and peanut oil. Moreover, palm oil contains a higher saturated fatty acid content than these five vegetable oils; thus, palm oil is a more efficient lubricant than the five other vegetable oils between the workpiece and the grinding wheel. However, the lubrication effect of palm oil is inferior to that of castor oil because the grinding force of the former is between those of the castor oil and the five other vegetable oils. The fluidity of palm oil does not differ significantly and some of the grinding heat is likely carried away by grinding fluid because palm oil exhibits a viscosity similar to soybean oil, rapeseed oil, corn oil, sunflower oil, and peanut oil. Therefore, palm oil-based MQL grinding possibly generates a relatively low grinding temperature.

3.3.3. Energy ratio coefficients of heat transferred into workpieces

The experimentally obtained energy ratio coefficients agree with the expected results. Among the vegetable oils, castor oil yields the highest energy ratio coefficient; by contrast, palm oil exhibits the lowest energy ratio coefficient. In terms of viscosity, fatty acid variety, and vegetable oil content, castor oil forms an effective lubrication film layer on the grinding wheel and workpiece surface because of its high viscosity and high ricinoleic acid content. Although this lubrication film reduces the grinding force, the film remarkably increases the grinding temperature and generates much heat. Therefore, the highest energy ratio coefficient of castor oil may be attributed to the high grinding temperature. As a result, the physical adsorption film and the metal saponification film fall off; thus, the formed adsorption film fails to protect the grinding zone completely and effectively. The generated grinding heat cannot be dispersed in time, and heat is mostly transferred into the workpiece because of the poor fluidity of castor oil. This characteristic is another factor contributing to the higher energy ratio coefficient of castor oil than that of other vegetable oils. The lowest energy ratio coefficient of palm oil may be obtained because palm oil generates less grinding heat as a consequence of its good cooling and lubrication effect; thus, the amount of heat transferred into the workpiece is reduced. Palm oil yields a viscosity similar to soybean oil, rapeseed oil, corn oil, sunflower oil, and peanut oil; thus, palm oil shows a similar fluidity in the grinding zone at a high temperature. However, the carbon chain of palm oil is shorter than those of the five vegetable oils; as a result, the heat transfer capacity of the grinding zone can be enhanced; palm oil can disperse heat in the grinding zone. Thus, palm oil can reduce the amount of heat transferred into the workpiece.

4. Conclusion

In this study, the MQL grinding performances of castor oil, soybean oil, rapeseed oil, corn oil, sunflower oil, peanut oil, and palm oil are compared. The following conclusions are obtained:

(1) Among the seven vegetable oils, castor oil generates the lowest grinding force but exhibits the highest grinding temperature and energy ratio coefficient. Palm oil yields the second lowest grinding force but shows the lowest grinding temperature and energy ratio coefficient. The five other vegetable oils share similar grinding forces, grinding temperatures, and energy ratio coefficients; the values range between those of castor oil and palm oil. Therefore, palm oil is identified as the optimum base oil of MQL grinding, with tangential and normal

grinding forces of 26.98 N and 87.10 N, respectively, a grinding temperature of 119.6 °C, and an energy ratio coefficient of 42.7%.
(2) Vegetable oils with higher viscosities elicit greater lubrication effects and significantly lower grinding forces. However, high viscosity reduces the heat exchange capability of vegetable oils; thus, a higher grinding temperature is obtained.
(3) Castor oil is compared with soybean oil, rapeseed oil, corn oil, sunflower oil, and peanut oil. The results reveal that viscosity affects grinding force and grinding temperature to a greater extent than fatty acid variety and content in vegetable oils. Saturated fatty acids are more efficient lubricants than unsaturated fatty acids.
(4) Among the vegetable oils, castor oil yields the highest energy ratio coefficient; by contrast, palm oil exhibits the lowest energy ratio coefficient. The viscosity of palm oil is lower than that of castor oil. Therefore, higher viscosity corresponds to a higher energy ratio coefficient of workpiece and weaker heat transfer effect. The energy ratio coefficient of palm oil is also compared with those of the five other vegetable oils. The results show that carbon chain length can affect the heat transfer capability of vegetable oils to a certain extent. A shorter carbon chain corresponds to a greater heat transfer effect.

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References

1. Li BM, Zhao B. Modern grinding technology. Beijing: China Machine Press; 2003. p. 5–7 [Chinese].
2. Jia DZ, Li CH, Zhang DK, Zhang YB, Zhang XW. Experimental verification of nanoparticle jet minimum quantity lubrication effectiveness in grinding. *J Nanopart Res* 2014;**16**(12):1–15.
3. Li X, Chen ZT, Chen WY. Suppression of surface burn in grinding of titanium alloy TC4 using a self-inhaling internal cooling wheel. *Chin J Aeronaut* 2011;**24**(1):96–101.
4. Khan AW, Wuyi C. Systematic geometric error modeling for workspace volumetric calibration of a 5-axis turbine blade grinding machine. *Chin J Aeronaut* 2010;**23**(5):604–15.
5. Malkin S, Guo C. Thermal analysis of grinding. *CIRP Ann Manuf Technol* 2007;**56**(2):760–82.
6. Jin T, Stephenson DJ. A study of the convection heat transfer coefficients of grinding fluids. *CIRP Ann Manuf Technol* 2008;**57**(1):367–70.
7. Zhang DK, Li CH, Zhang YB, Jia DZ, Zhang XW. Experimental research on the energy ratio coefficient and specific grinding energy in nanoparticle jet MQL grinding. *Int J Adv Manuf Technol* 2015;**78**(5–8):1275–88.
8. Zhang DK, Li CH, Jia DZ, Zhang YB, Zhang XW. Specific grinding energy and surface roughness of nanoparticle jet minimum quantity lubrication in grinding. *Chin J Aeronaut* 2015;**28**(1):570–81.
9. Jia DZ, Li CH, Wang S, Zhang Q, Hou YL. Advances and patents about grinding equipments with nano-particle jet minimum quantity lubrication. *Recent Pat Nanotechnol* 2014;**8**(3):215–29.
10. Wu KZ, Chen YJ, Zhu DD. The dry cutting technology and its tools. *Cem Carbide* 2005;**22**(1):47–50 [Chinese].
11. Hou YL, Shang SS, Gu LZ, Li CH. Green machining technology. *Precise Manuf Autom* 2007(4);19–22 [Chinese].
12. Pei HJ, Zhang CY, Zhang WW. MQL machining trace cooling lubrication system. *China Manuf Ind Inf* 2007;**36**(19):136–42 [Chinese].
13. Shi CF, Li X, Chen ZT. Design and experimental study of a micro-groove grinding wheel with spray cooling effect. *Chin J Aeronaut* 2014;**27**(2):407–12.
14. Li CH, Wang S, Zhang Q, Jia DZ. Evaluation of minimum quantity lubrication grinding with nano-particles and recent related patents. *Recent Pat Nanotechnol* 2013;**7**(2):167–81.
15. Li CH, Han ZL, Zhang Q, Wang S. Modeling and experimental investigation of pressure field in the grinding zone with nanoparticle jet of MQL. *Adv Mech Eng* 2013;1–15.
16. Barczak LM, Batako ADL, Morgan MN. A study of plane surface grinding under minimum quantity lubrication (MQL) conditions. *Int J Mach Tools Manuf* 2010;**50**(11):977–85.
17. Hadad MJ, Tawakoli T, Sadeghi MH, Sadeghi B. Temperature and energy partition in minimum quantity lubrication-MQL grinding process. *Int J Mach Tools Manuf* 2012;**54–55**:10–7.
18. Dhar NR, Ahmed MT, Islam S. An experimental investigation on effect of minimum quantity lubrication in machining AISI 1040 steel. *Int J Mach Tools Manuf* 2007;**47**(5):748–53.
19. Gaitondea VN, Karnikb SR, Paulo DJ. Selection of optimal MQL and cutting conditions for enhancing machinability in turning of brass. *J Mater Process Technol* 2008;**204**(1–3):459–64.
20. Mao C, Zou HF, Huang Y, Li YF, Zhou ZX. Analysis of heat transfer coefficient on workpiece surface during minimum quantity lubricant grinding. *Int J Adv Manuf Technol* 2013;**66**(1):363–70.
21. Tawakoli T, Hadad MJ, Sadeghi MH, Daneshi A, Stöckert S, Rasifard A. An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication-MQL grinding. *Int J Mach Tools Manuf* 2009;**49**(12):924–32.
22. Silva LR, Bianchi EC, Fusse RY, Fusse RY, Catai RE, Franca PR, Aguiar PR. Analysis of surface integrity for minimum quantity lubricant-MQL in grinding. *Int J Mach Tools Manuf* 2007;**47**(2):412–8.
23. Ding WF, Xu JH, Chen ZZ, Su HH, Fu YC. Grindability and surface integrity of cast nickel-based superalloy in creep feed grinding with brazed CBN abrasive wheels. *Chin J Aeronaut* 2010;**23**(4):501–10.
24. Steigerwald SR. Vegetable oil improve the processing performance. *Manuf Eng* 2005;**4**:76–7.
25. Zhang YB, Li CH, Jia DZ, Zhang DK, Zhang XW. Experimental evaluation of MoS_2 nanoparticles in jet MQL grinding with different types of vegetable oil as base oil. *J Clean Prod* 2015;**87**:930–40.
26. Nurul AMJ, Kamaleshwaran T, Ahamd FM, Azwan IA. A study of surface roughness and surface integrity in drilling process using various vegetable-oil based lubricants in minimum quantity lubrication. *Aust J Basic Appl Sci* 2014;**8**(15):191–7.
27. Cetin MH, Ozcelik B, Kuram E, Erhan D. Evaluation of vegetable based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L by Taguchi method. *J Clean Prod* 2011;**19**(17–18):2049–56.
28. Mohamed HSE, Kurniawan D, Noordin MY. Use of castor oil as cutting fluid in machining of hardened stainless steel with minimum quantity of lubricant. *Procedia CIRP* 2015;**26**:408–11.

29. Le TS, Tran MD, Nguyen DB, Nguyen VC. An investigation on effect of characteristics of the peanut oil MQL on tool life in hard turning 9CrSi steel. *Int J Mach Mater* 2013;**4**(13):428–38.
30. Jain A, Bisht RPS. Metalworking emulsions from industrial vegetable oils. *J Synth Lubr* 2008;**25**(3):87–94.
31. Rahim EA, Sasahara H. An analysis of surface integrity when drilling inconel 718 using palm oil and synthetic ester under MQL condition. *Mach Sci Technol* 2011;**15**(1):76–90.
32. Rahim EA, Sasahara H. Investigation of tool wear and surface integrity on MQL machining of Ti–6AL–4V using biodegradable oil. *Proc Inst Mech Eng Part B J Eng Manuf* 2011;**225**(9):1505–11.
33. Rahim EA, Sasahara H. A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. *Tribol Int* 2011;**44**(3):309–17.
34. Parash K, Ajay PM, Kumar SA, Yoganath VG, Gurumurthy T. Study of specific energy and friction coefficient in minimum quantity lubrication grinding using oil-based nanolubricants. *J Manuf Processes* 2012;**14**(2):160–6.
35. Nguyen TK, Do I, Kwon P. A tribological study of vegetable oil enhanced by nano-platelets and implication in MQL machining. *Int J Precis Eng Manuf* 2012;**13**(7):1077–83.
36. Khan MMA, Mithu MAH, Dhar NR. Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. *J Mater Process Technol* 2009;**209**(15):5573–83.
37. Belluco W, Chiffre LD. Performance evaluation of vegetable-based oils in drilling austenitic stainless steel. *J Mater Process Technol* 2004;**148**(2):171–6.
38. Malkin S, Cook NH. The wear of grinding wheels: Part 1–attritious wear. *J Manuf Sci Eng* 1971;**93**(4):1120–8.
39. Malkin S. Grinding technology theory and application. Shenyang: Northeastern University Press; 2002. p. 90.
40. Zhang DK. Mechanism and experimental study of nanoparticle jet MQL grinding high temperature nickel-based alloys convective heat transfer [dissertation]. Qingdao: Qingdao Technological University; 2014 [Chinese].
41. Outwater JO, Shaw MC. Surface temperature in grinding. *Trans ASME* 1952;**12**(1):73–8.
42. Guo C, Malkin S. First international conference on transport phenomena in processing. *Heat transfer in grinding*. Western Hemisphere: Technomic Publishing Company Inc.; 1992. p. 377.
43. Zhang JB. Lubrication of machinery and equipment. *Plant Maintenance Eng* 2012(S1);65–71 [in Chinese].
44. Hu ZM. *Vegetable oil fatty acids, hydroxy and sulfide tribology research*. Shanghai: Shanghai University Press; 1999. p. 36–40 [Chinese].
45. Hu Y, Dang HX, Liu WM, Chen JM. Friction characteristics of vegetable oil fatty acids. *Lubr Oil* 2000;**15**(4):38–40 [Chinese].
46. Zhang YB, Li CH, Jia DZ, Zhang DK. Experimental evaluation of nanoparticles in jet MQL grinding nickel-based alloys. *Modular Mach Tool Autom Manuf Tech* 2015;**6**:113–7 [Chinese].

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